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Condition Monitoring of Lubricant in Static Mechanisms Using Pulse-Echo Ultrasound Technique

Marwan Ali[a*], Milan Simic[b], Fadi Imad[c], Farrukh Nagi[d]

[a,b]*School of Engineering, RMIT University, Melbourne,vic, 3083, Australia*
[c,d]*School of Engineering Universiti Tenaga Nasional, Selangor, 43000, Malaysia*

Abstract

This paper proposes an active pulse-echo ultrasonic testing method to determine the lubricant condition in static mechanical components and assemblies. An ultrasonic inspection system was constructed to produce and receive back, high frequency ultrasonic pulses. Wavelet transform was used to de-noise the acquired signal and extract features from the feedback waveforms. Features data, from different samples, were analyzed and used to develop a fuzzy inference system to define the lubricant condition. Classification system was then examined, using grease samples, with known condition. The results indicated that the novel pulse-echo technique is a suitable method for the inspection of lubricants condition in various engineering systems.

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Keywords: Condition monitoring; Ultrasonic; wavelet

1. Introduction

Lubricating oil ensures that moving parts which interact within a machine system are provided with the required level of contact separation. Further lubricants are used to reduce friction and to prevent destructive wear. Even finely machined metal surfaces have microscopically rough surfaces that will cause some friction when in contact. The lubricant systems minimize this wear by providing separation, cooling and surface protection. Therefore, without these systems, machine will suffer from increased friction, heat resulting in damages such as local welding, scuffing, seizing and the undesirable transfer of metal debris[1].

*Corresponding author. Tel.: +61-450-700-333.
E-mail address: Marwan.ali@rmit.edu.au

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Movement of mechanical parts produces a wide spectrum of sound consisting of low frequencies audible sound which can be detected by human ear. Other emissions, of high frequencies, are inaudible for human ears to hear, but can be detected using ultrasonic measuring systems. The changes in amplitude and frequency of these waves can give an indication of how severe is the friction between the mechanical parts [2]. Consequently, this led to the invention of the grease caddy. Grease caddy is a giant leap forward in lubrication technology which allowed machine operators to simultaneously lubricate and monitor ultrasound levels to prevent over-lubrication. Furthermore, it assisted machine owners to shift away from traditional time based re-greasing schedules to condition based re-greasing schedules. However, there are mechanical systems which are static but are charged (compressed springs) and ready to respond to external trigger. Examples of such systems are spring actuated high voltage circuit breakers, safety valves, latches and hooks with retracting springs. Normally these devices are actuated by stored spring energy and have numerous moving mechanical parts which are to remain lubricated over extended periods of time and are expected to perform the task upon external triggering event. For instance, a circuit breaker is to trip in milliseconds upon receiving the triggering signal to prevent damage to electrical appliances. Due to the nature of operation, these devices remain static for long periods of time which leads the grease to dry up and cause the device to fail, or show sluggish response when receiving the triggering signal. This will result in damages, black outs and power outages. Those devices will remain static and will not emit any acoustic emission. Thus the monitoring of their condition using the earlier method becomes a tedious task that requires triggering of such systems which disturbs the power supply in the case of circuit breakers.

1.1 Review & Background Study

In general there are two ultrasonic evaluation methods for lubricants. The first one is passive testing method, which depends on listening to acoustic emissions, and the second one is active testing method which depends on sending an ultrasound pulse and listening to the echoes. Most of the research in ultrasonic lubricant condition monitoring utilized the passive acoustic emission measurement method, such as the investigation done by Miettinen [3]. The finding from this research established that lubricant-film monitoring, through ultrasonic acoustic emission measurement technique, provides early warning of bearing failure. In ball bearings, as used in raceway, roller, or bearing balls begin to fatigue. A slight deformation begins to occur causing friction and thus resulting in acoustic emission. During the process of measuring those emissions, the suitability, quantity and quality of the grease for the application were examined. Although this method is effective for dynamic systems such as rotating bearings, it is not suitable for static systems since they do not emit any acoustic noise signals. Meanwhile, some other researchers utilized the pulse echo method to determine properties of a thin oil film as done by Dwyer-Joyce et al. [4] and Kasolang & Dwyer-Joyce [5], where the thickness and the viscosity of an oil sample were realized from the proportion of incident signals reflected. Shear wave ultrasonic pulses were produced to penetrate the lubricated piece, portion of the pulse reflects from the surface of the oil and other portion penetrates depending on the impedance mismatch between the piece and the oil. The proportion is known as the reflection coefficient, *R* and can be related to the impedances of the two materials according to [6]:

$$R = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1} \right)^2 \tag{1}$$

Where Z_2 and Z_1 are the acoustic impedances of the oil and plates material respectively. The impedance of the oil can be used to find physical properties of the oil. The drawback of this technique is that the one of the properties, either viscosity or film thickness, should be known, to get the other property. This technique is not suitable for testing lubricants in service when both lubricant thickness and viscosity are variable in such conditions. A very similar method to the approach sought have been utilized in research carried out by Kouki Nagamune et al [7] to evaluate the degradation of insulating oil in transformers using two transducers (pulsar and receiver). During the evaluation process, a pulse was transmitted from the pulsar while the receiver captures the passing wave and its echoes. Fuzzy inference system is used to estimate the kinetic viscosity of the oil. The method showed a correlation coefficient of over 0.92 with the viscometer readings. However, due to oil container having fixed and large dimensions, this method is not valid for applications where lubricant film thickness is variable and tiny such as the case studied.

2. Experimental Work

Ultrasonic inspection system equipment was set up as shown in Fig 1. Equipment used included ultrasonic pulsar/receiver (panametrics 5072PR) and 10 MHz longitudinal transducer. The pulsar/receiver generates voltage pulses up to 400V to make the piezoelectric crystal of the transducer oscillate producing ultrasound. The pulsar/receiver also receives the reflected pulse from the transducer and amplifies it. An oscilloscope was used to capture and digitize the waveform so it can be viewed and loaded into the computer. Ultrasonic pulsar/receiver was connected to the transducer and the appropriate frequency has been set. "RF OUT" port was connected to the "Channel 1" in the oscilloscope to transfer the ultrasonic signal. To keep the signal synchronized, "SYNC OUT" port was connected to the "External Trigger" of the oscilloscope. Finally the oscilloscope was connected to the computer using RS232 null cable to load the graph data into the PC.

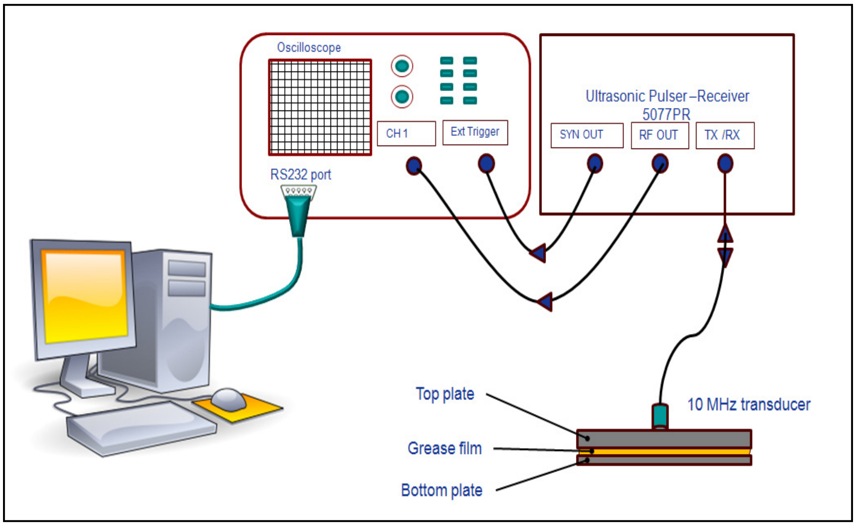

Fig.1. Ultrasonic inspection system

2.1 Communicating with the Oscilloscope

Set of Standard Commands for Programmable Instruments (SCPI) is an instrument command language introduced in 1999. It is used to control a variety of instrument functions such as frequency and voltage in a standard manner. SCPI defines dedicated commands available for those functions. Therefore, two oscilloscopes from different manufacturers can be used to make frequency measurements in the same way [8]. As the oscilloscope used has a serial port, these commands can be sent to the oscilloscope through serial port using HyperTerminal. However, since MATLAB is used for the data processing, it is better to use MATLAB to send the command lines through the serial port. The use of MATLAB software in acquiring data, as well as processing, helps in automating the whole process by writing one script which does the entire process and displaying only the final result of the inspection.

2.2 Samples preparation

Samples consist of three types of greases; two simple lithium greases and one, complex lithium grease, with properties as shown in Table 1. Experiments were carried out by placing same amount (mass) of grease between two aluminum plates. The top plate is thicker than the bottom plate, with thickness of 2.0cm and 0.5cm respectively. This is to allow the wave reflected from the interface of bottom plate and air to pass without overlapping with the wave reflected from the interface of top plate and grease. Grease tends to cake and dry out due to the natural tendency of oil to drain out of the grease thickener over the time [9]. In order to simulate this process, each type of grease sample was aged by heating the plates in three levels using a furnace oven set at temperatures 100, 200^0C and 300°C for 5 hours each. Subsequently, this leads to thermal run away. When the dropping point is achieved, the base oil begins to bleed and the grease runs dry after it is cool. Although the dropping point of the Lubrimatic and Abro greases is much lower compared to Pennzoil, it was found that at 300°C the reflected ultrasound has different features due to the leaching, dryness and cracking of the remaining soap. At 300°C, black and blue greases do not follow the same pattern due to its low dropping point. Consequently, they were heated up to 250°C only. Ultrasonic waves of 10 MHz were then applied, on the top plate of different samples, and the reflected waves were recorded as displayed in Fig 2.

Table 1. Properties of different greases used

Property	Pennzoil Grease	Lubrimatic Grease	Abro Grease
Soap type	1. Lithium complex	2. Lithium	3. Lithium
Dropping point	4. 272°c	5. 177°c	6. 183°c
Base oil	7. Mineral	8. Mineral	9. Mineral
Color	10. Yellow	11. Carbon Black	12. Blue

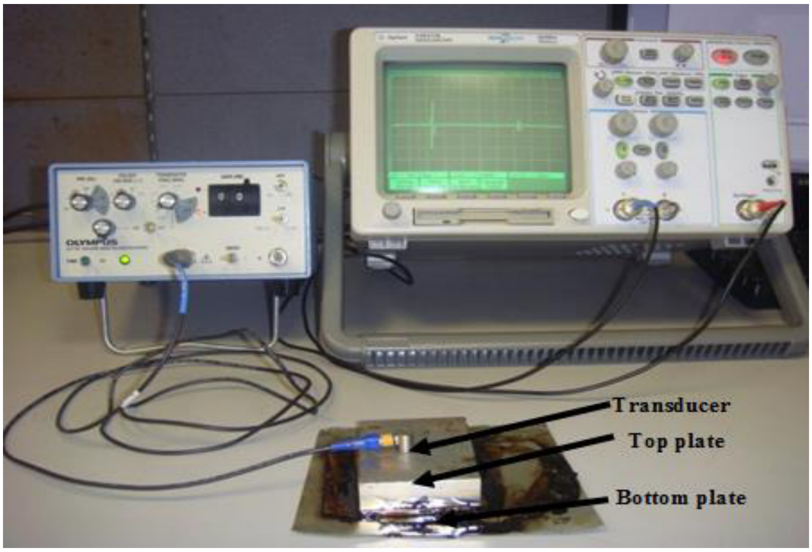

Fig.2. Photograph of the experiment apparatus. The leaching oil after aging is visible bellow the sample.

3. Analysis and results

3.1 Raw signal

The raw signals received from ultrasonic inspection system are shown in Fig 3. Signal waveform has peaks which represent the reflections from the sample after the initial pulse.

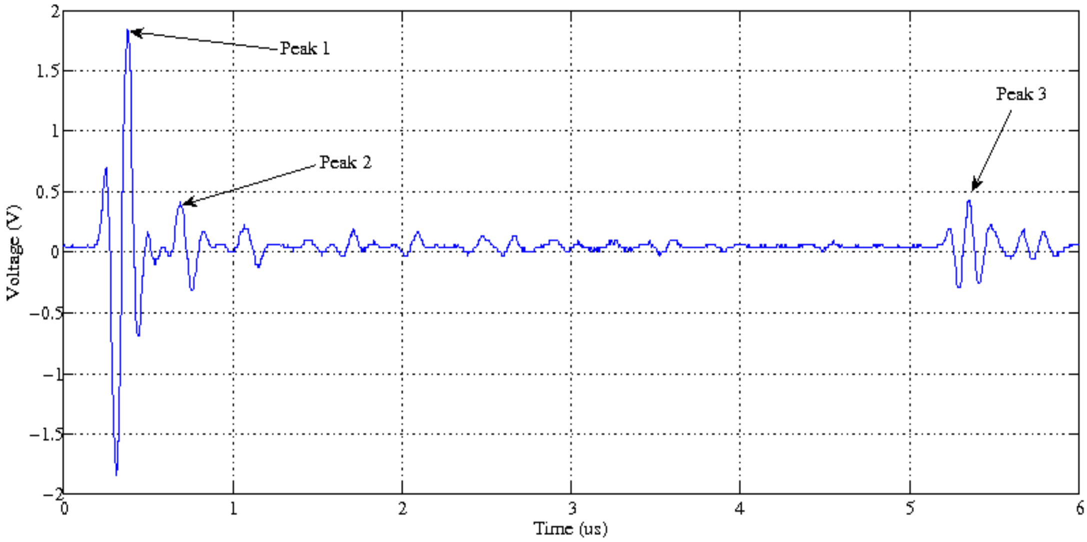

Fig.3. Raw ultrasonic signal for lubrimatic grease aged at 200°c for 5 hours.

The peak labeled as peak 1 in Fig 3 is the ultrasound wave reflected from the interface between the top plate and the grease film, whereas, peak 2 is the ultrasound wave reflected from the interface between the bottom plate and the air below. Finally, peak 3 is the one of the multiple reflections of peak 1, and this was verified using the following relation [10]:

$$T = \frac{2x}{c} \tag{2}$$

Where T is time of flight, x is the thickness of the aluminum plate and c is the sound velocity in aluminum. The calculated time of flight was found to be equal to half of the time between peak 1 and peak 3 from the waveform in Fig.3 as expected. There are other small peaks between peaks 2 and 3 which are the multiple reflections of peak 2. As peaks 1 and 3 show reflections of ultrasonic pulses which did not penetrate the grease, they do not carry the features of the grease which are required.

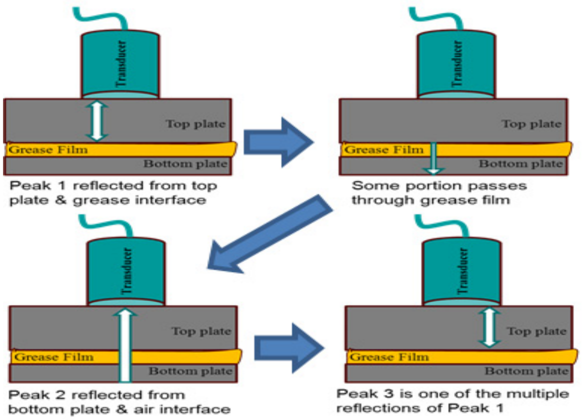

Fig.4. Reflection of ultrasonic signals from the interfaces

Peak 2 and its multiple reflections carry the desired features. The obvious pattern of the amplitude of peak 2 with the aging period can be seen between three different samples as shown in Table 2. Aged grease samples tend to have higher amplitude due to less attenuation during sound waves transfer in the solid objects compared to liquid objects. As the grease solidifies, the reflected ultrasound waves from the bottom plate become larger. It is noticed that for the yellow grease, the amplitude values remain the same for the grease aged at 100°C as well as the new grease. This is due to the lithium complex grease having a dropping point as high as 272°C. In addition, the reflection time for peak 2 also decreases with the aging process due to two main factors. Firstly, the reduced thickness of the grease film shifts the peak to the left. This happens as the grease is settling down, when heated, and due to oil bleeds. The formula, which governs these phenomena and explains the change of amplitude of a wave through material, is:

$$A = A_O e^{-\propto z} \tag{3}$$

Where A_0 represents the initial amplitude, α is the attenuation coefficient and z is the traveled distance. The second factor that decreases peak 2 times during aging process is the speed of the ultrasound, which moves faster in the solidified grease than the wet grease. This is due to the fact that solids have a very high viscosity level compared to liquids and gases. The attenuation coefficient is also proportional to the dynamic viscosity η according to the Stocks law of attenuation which states:

$$\propto = \frac{2\eta\omega^2}{3\rho c^3} \tag{4}$$

Where η is the dynamic viscosity, ω is sound frequency, ρ is the density and c is the speed of sound. Thus the attenuation of ultrasound waves can provide an indication of the grease condition.

Table 2. Raw signal features

Grease type	Aging temperature	Peak Amplitude (V)	Peak Time (μs)
Pennzoil yellow	**New**	0.09375	4.990
	100 °C	0.09375	4.510
	200 °C	0.18750	3.430
	300 °C	0.34380	2.850
Lubrimatic black	**New**	0.12500	5.235
	100 °C	0.21880	3.735
	200 °C	0.40630	2.690
	250 °C	0.50000	2.630
Abro blue	**New**	0.09375	4.925
	100 °C	0.09375	4.875
	200 °C	0.28130	3.290
	250 °C	0.31250	2.620

3.2. Wavelet Signal Processing

The part of the signal of interest is between the peaks 1 and 3 because it carries the required features. In order to extract the features and de-noise the signal, continuous wavelet transform was applied on that part of the signal according to the Equation 5.

$$\gamma(s,\tau) = \frac{1}{\sqrt{s}} \int_{-\infty}^{\infty} f(t)\Psi\left(\frac{t-\tau}{s}\right)dt \tag{5}$$

Where *f(t)* is the signal to be transformed, *s* is the change in scale, τ is shift in time and ψ is the mother wavelet used. A proper mother wavelet was chosen to match the ultrasonic reflected pulse as similar as possible. This was confirmed by applying cross correlation between the reflected pulse and the mother wavelet to see which wavelet gives the maximum correlation coefficient. Daubechies 4 mother wavelet was chosen because it closely matched the ultrasonic reflected pulse after normalization and scaling, achieving a correlation coefficient of 0.8693 as shown in Fig 5.

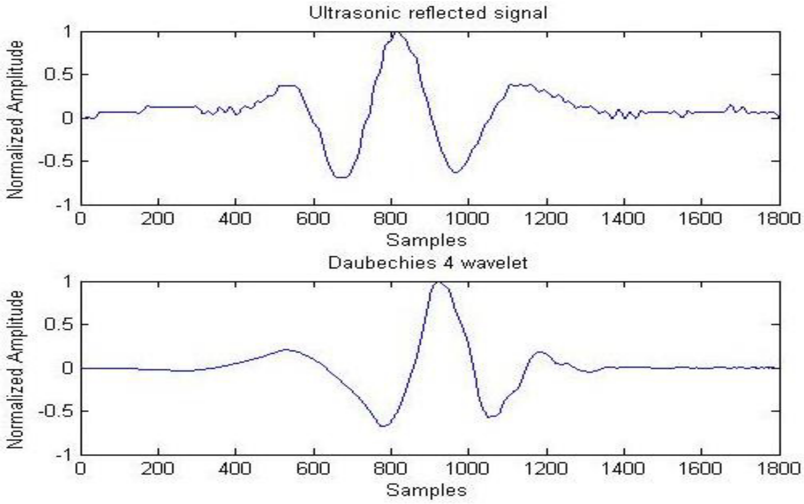

Fig.5. Correlation between ultrasonic pulse and Daubechies 4 wavelet

The raw signal had high frequency noise spikes while the wavelet transformed signal had the signal decomposed to several frequencies with the noise situated at high frequencies (small scales) and the information signal at lower frequencies (small scales) as shown in Fig 6.

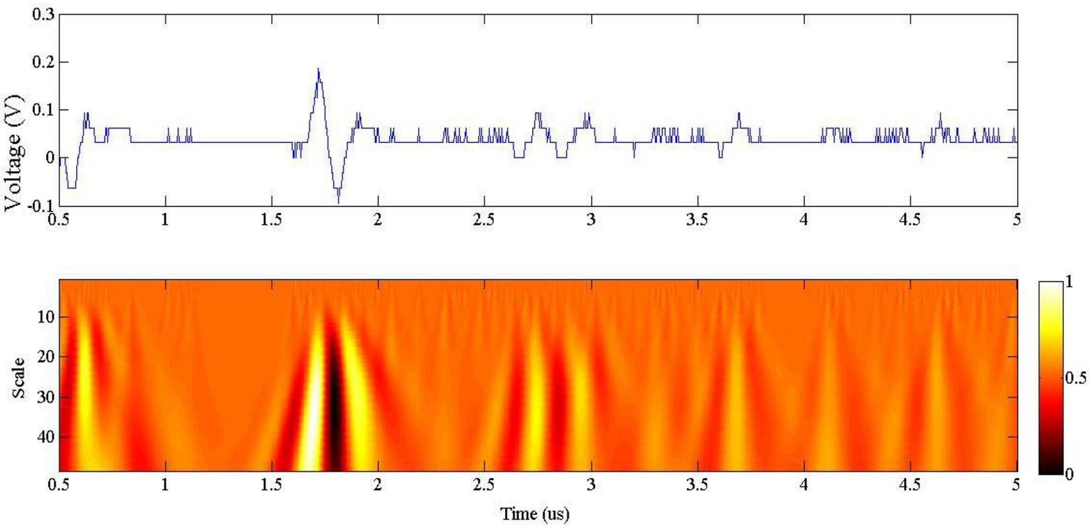

Fig.6. Wavelet transform of signal for Pennzoil Grease aged at 200°c.

The amplitudes, times and scales at the highest coefficient of each sample were recorded as features and can be seen in Table 3. There is a noticeable pattern between the features and the aging temperatures of the samples. Coefficient and time exhibit the same pattern as before the wavelet transform but a scale was introduced. The scale is the reverse of the frequency, so the drier the grease samples are, the higher the ultrasonic frequency that passes through, which gives smaller scale values.

Table 3. Wavelet peak signal features

Grease type	Aging temperature	Coefficient	Scale	Frequency (MHz)
Pennzoil yellow	New	0.2934	41	3.48
	100 °C	0.2683	41	3.48
	200 °C	0.4953	36	3.97
	300 °C	0.999	27	5.29
Lubrimatic black	New	0.3766	34	4.2
	100 °C	0.6447	30	4.76
	200 °C	1.1916	27	5.29
	250 °C	1.3176	25	5.71
Abro blue	New	0.2170	44	3.25
	100 °C	0.2322	41	3.48
	200 °C	0.8332	30	4.76
	250 °C	0.8682	22	6.49

3.3 Development of fuzzy classification system

Mamdani fuzzy inference system was used in the classification of grease condition. All available sample data sets were plotted on coefficient versus scale graph, which representing the feature space. The time was not plotted because it depends more on the film thickness than the age of the sample. After the feature space was plotted, it was partitioned according to the actual age of the grease sample as shown in Fig 7.

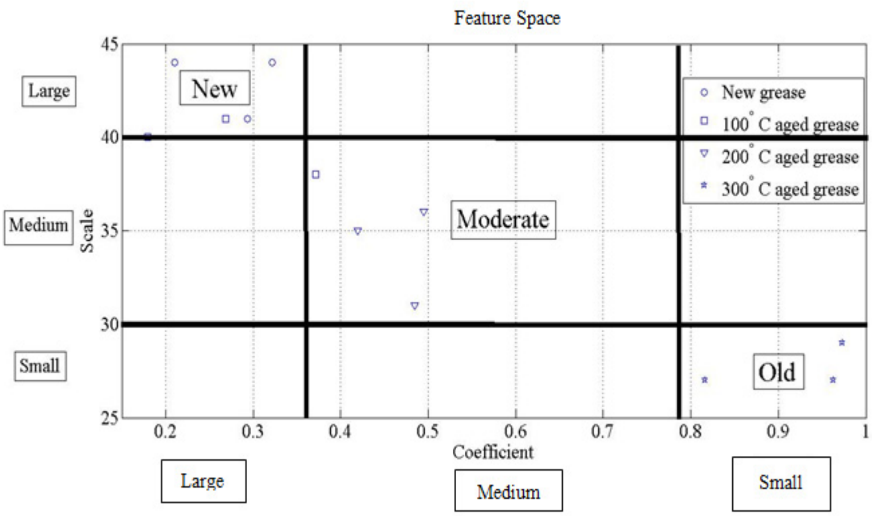

Fig.7. Partitioned features space.

Different feature classes were situated in separate partitions as this allows high interpretability and easy definition of fuzzy rules. The fuzzy membership functions have been designed based on the borders between classes. The intercept points of membership functions were defined by the class borderlines. Three output weights 0, 50 and 100 have been chosen to represent the new, medium and old conditions of the grease respectively. Following the partition of the feature space and design of membership functions, the fuzzy rules were determined by relating membership functions of the input to the output which is the age of the grease sample. As the feature space is partitioned into 9 spaces, 9 fuzzy rules were set to decide the grease condition as shown in Table 4.

Table 4. Fuzzy rules table.

Coefficient	Scale		
	Small	**Medium**	**large**
Small	Old	New	New
Medium	Moderate	Moderate	Old
Large	Old	Old	Old

3.4 Inspection System Testing and Validation

The full inspection procedure of the grease was validated in two ways. Firstly, stored ultrasonic waveforms from the sample were used to test the algorithm and secondly, testing was done through real time inspection of the specimen. The routine which does the processing and classification was tested using signals stored in the workspace similar to the signal shown in Fig 8. Initially wavelet transform was applied to the signal which resulted in the scalogram graph as shown in Fig 9. After that, the coefficient and scale were extracted from the signal and then fed into the fuzzy classification system which determines the percentage of newness. The newness percentage was then translated into grease condition. A sample of the testing process results can be viewed in Fig 10. Out of 16 samples tested, 12 gave the results that match the actual condition observed. Two of the 4 samples which were misclassified gave features that are out of the range from the fuzzy classification system, while the other 2 were misclassified due to crossing the line into the adjacent partition in the feature space. Furthermore, real time inspection was done using a programming routine which acquires the signal, then processes it and classifies. Real time inspection results show similarity to the ones achieved from the test using stored signals. The system operated within the same range of accuracy and in most cases interpreted the actual condition of the grease inspected.

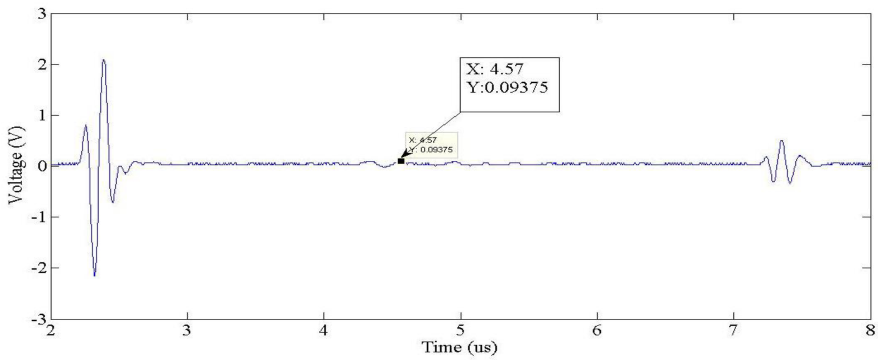

Fig.8. Raw ultrasonic signal

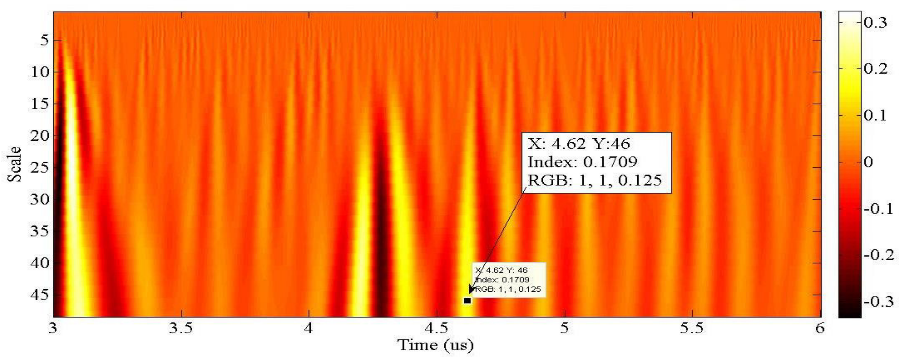

Fig.9. Wavelet transformed signal

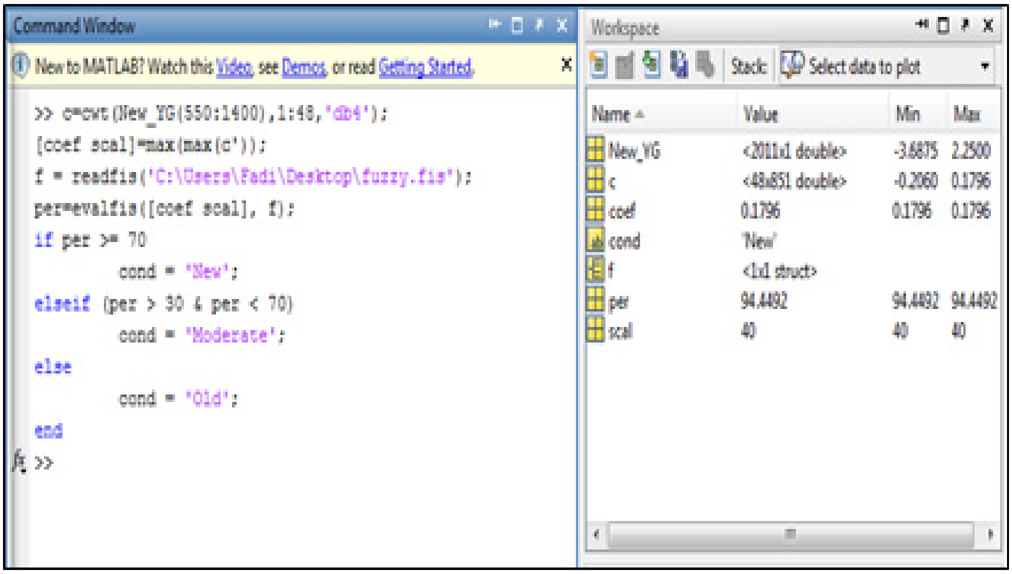

Fig.10. New grease inspection results.

4. Conclusion

The grease aging process has been experimentally analyzed using ultrasound pulse-echo technique. The ultrasonic signal was then processed with wavelet technique to yield features coefficient and scale. The coefficients represent the attenuation values due to grease dampness while the scales represent the frequencies that passed through the grease. Grease samples were then classified using fuzzy system that uses the features as an input to interpret the grease condition. The results achieved have proven that the designed system has achieved inspection accuracy up to 75%. The attained results indicate that our novel pulse-echo technique can be utilized effectively to determine the condition of each type of grease. Method presented here has its possible applications in various mechatronics devices, vehicles and intelligent transportation systems.

References

1. Greg J. Livingstone and Brian T. Thomson 'Effective Methods for Determining the Root Causes of Fluid Degradation ', Lubrication Excellence Conference - May; 2006.
2. Victor M. Baranov, Evgeny M. Kudryavtsev, Gennady .A. Sarychev, Vladimir M. Schavelin' Acoustic Emission in Friction' First Edition, Elsevier; 2007, p. 10-15.
3. Miettinen, J., Andersson, P., and Wikstrom, V., "Analysis of grease lubrication of a ball bearing using acoustic emission measurement," Proc ImechE, Part J: J. Engineering Tribology., 215(6), 2001, p. 535-544.
4. Dwyer-Joyce, R.S., Drinkwater, B.W., and Donohoe, C.J., "The Measurement of Lubricant Film Thickness using Ultrasound", Proc. R. Soc. Lond., 459A, 2002,pp. 957-976.
5. Kasolong S and Dwyer-Joyce RS., "Viscosity measurement in thin lubricant film using shear ultrasonic reflection". Proc ImechE, Part J: J. Engineering Tribology, 222, 2008, p.423-429.
6. Krautkramer, J., and Krautkramer, H. Ultrasonic Testing of Materials, Sringer-Verlag, New York; 1990.
7. Kouki Nagamune, Syoji Kobashi, Katsuya Kondo, and Yutaka Hata," An ultrasonic Evaluation For Degradation Of Insulating Oil using Fuzzy Inference", IEEE Ultrasonics Symposium, 2003, pp.893-896.
8. "Standard Commands for Programmable Instruments (SCPI)", Volume 1: Syntax and Style, May, 1999.
9. Lawrence G. Ludwig, Schaeffer Mfg. Company, Practicing Oil Analysis Journal, February 2012, "Storing Grease to Avoid Bleed and Separation", http://www.machinerylubrication.com/Read/28761/storing-grease-to-avoid-bleed-separation-. Accessed on May; 2012.
10. William R. Hendee and E. Russell Ritenour, "Medical Imaging Physics", Fourth Edition, New York: Wiley-Liss, 2002.